Chapter 54
Modified Higgs Couplings in the Minimal Composite Higgs Model and Beyond

Avik Banerjee

Abstract Composite Higgs scenario, where the Higgs boson emerges as a pseudo-Nambu-Goldstone boson (pNGB), is well motivated as an approach to solve the Hierarchy problem of the Standard Model. One of the main phenomenological consequences of this setup is sizable deviations of the Higgs couplings from their Standard Model predictions. We discuss how the modification of the Higgs couplings with weak gauge bosons and quarks arise in the minimal composite Higgs model and its impact on the scale of compositeness. We take an effective field theoretic approach to illustrate our results. The coupling modifications in models beyond the minimal scenario where the scalar sector is extended with Standard Model singlets and triplets are also discussed.

54.1 Introduction

The discovery of the Higgs boson at the Large Hadron Collider (LHC) paved the path towards the precision study of the properties and origin of the Higgs. Several motivated beyond the Standard Model (BSM) scenarios predict deviations of the Higgs couplings compared to their Standard Model (SM) values. These deviations can in principle be tested at the LHC and proposed future colliders and yield significant information about the nature of the Higgs boson. Composite Higgs models [1, 2] provide an alternative to supersymmetry to solve the Hierarchy problem of SM. It consists of a framework where the Higgs boson originates as a pseudo-Nambu-Goldstone boson (pNGB) of a strong sector with spontaneously broken global symmetry (analogous to the pions in QCD) [3–5]. The scale at which the strong sector condenses sets the geometric dimension of the composite Higgs and is known as the scale of compositeness (f). The SM gauge bosons and fermions, on the other hand,

Avik Banerjee—Speaker. Work done in collaboration with Gautam Bhattacharyya, Nilanjana Kumar and Tirtha Sankar Ray.

A. Banerjee (✉)
Saha Institute of Nuclear Physics, HBNI, 1/AF Bidhan Nagar, Kolkata 700064, India
e-mail: avik92kol@gmail.com

P. K. Behera et al. (eds.), *XXIII DAE High Energy Physics Symposium*,
Springer Proceedings in Physics 261,
https://doi.org/10.1007/978-981-33-4408-2_54

are elementary and their interaction with the strong sector *resonance* states via linear mixing explicitly breaks the global symmetry. This endows the Higgs boson with a potential and is responsible for the electroweak symmetry breaking. The couplings of the Higgs in this scenario are modified due to the strong dynamics compared to the corresponding SM values, and the measurements of the Higgs couplings at LHC, in turn, put stringent limits on the scale of compositeness. However, in the absence of any signal of new physics at the LHC, effective field theoretic frameworks become more popular in the study of Higgs boson [6]. The idea behind using an effective theory is that the effect of new dynamics appearing at a high scale can be captured by constructing higher dimensional operators, which respect symmetries at low energies. The higher dimensional operators contribute to the modifications of the couplings of the Higgs boson with other SM particles.

The other yet unknown aspect of the electroweak symmetry breaking is the full constituents of the scalar sector. Apart from the usual $SU(2)_L$ doublet Higgs, additional singlet, doublet or triplet scalars can exist. The presence of the additional scalars also modifies the couplings of the 125 GeV Higgs boson. Moreover, these scenarios contain other neutral and charged scalars with different CP eigenstates providing interesting phenomenological consequences.

In what follows, we discuss the modifications of Higgs coupling in composite Higgs setup (Sect. 54.2). We also show the use of the strongly interacting light Higgs framework to construct the higher dimensional operators and calculate the coupling modifiers. Then we discuss some models with extended scalar sectors and show how the couplings of the Higgs boson changes in those cases (Sect. 54.3). Finally, we conclude (Sect. 54.4).

54.2 Minimal Composite Higgs Model (MCHM)

The minimal realization of the composite Higgs setup, compatible with electroweak precision constraints, consists of a coset SO(5)/SO(4) producing four pNGBs [7]. In the unitary gauge, the pNGB Higgs can be parametrized as

$$\Sigma = (0,\ 0,\ 0,\ s_h,\ c_h)^T\ , \tag{54.1}$$

where $s_h \equiv \sin(h/f)$, $c_h \equiv \cos(h/f)$. The gauge interactions of the pNGB Higgs with SM gauge bosons are given by

$$\mathcal{L}_{\text{gauge}} \simeq \frac{g^2 f^2}{4} \sin^2\left(\frac{h+V}{f}\right)\left[W^+_\mu W^{\mu-} + \frac{1}{2\cos^2\theta_w} Z_\mu Z^\mu\right]. \tag{54.2}$$

While the masses of gauge bosons set the definition of the electroweak vacuum expectation value (vev) as

$$v_{\text{EW}} = f \sin\frac{V}{f}\ , \tag{54.3}$$

the couplings of the physical (125 GeV) Higgs boson with the weak gauge bosons ($V = W^{\pm}, Z$) get modified as follows:

$$k_V = \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \sqrt{1-\xi}\,, \tag{54.4}$$

where $\xi = v^2/f^2$. It is worth noting that the modification factor depends only on the scale of the compositeness and this feature is in general true for any SO(N)/SO$(N-1)$ coset.

The modifications of the Yukawa couplings, on the other hand, depends on the representations of SO(5) in which the SM fermions are embedded. The *partial compositeness paradigm* implies that the SM fermions couples to the Higgs boson through a linear mixing with some strong sector operators. This means, after the condensation of the strong sector, the mass eigenstates are the linear superposition of elementary and composite resonance states. To fulfill the requirement of assigning the correct hypercharge of the SM fermions, an additional unbroken $\mathrm{U(1)_X}$ is customarily introduced. For the purpose of illustration, we consider only the embeddings of the SM fermions (specifically top quark) in the fundamental **5** and symmetric **14** of SO(5). Decomposition of $\mathbf{5_{2/3}}$ of SO(5) $\times\, U(1)_X$ under the SM gauge group is given by

$$\mathbf{5}_{2/3} \rightarrow 2_{7/6} \oplus 2_{1/6} \oplus 1_{2/3}\,. \tag{54.5}$$

We present the relevant incomplete multiplets for left- and right-handed top quarks in the so-called $\mathrm{MCHM}_{5_L-5_R}$ model as [4]

$$Q_L^5 = \frac{1}{\sqrt{2}}(-ib_L, -b_L, -it_L, t_L, 0)^T, \quad T_R^5 = (0,0,0,0,t_R)^T\,. \tag{54.6}$$

The only SO(5) invariant term (involving Q_L^5, T_R^5 and Σ), constituting the effective low energy Yukawa Lagrangian can be written as

$$\mathcal{L}_{\rm Yuk} = \Pi_{LR}(q^2)(\overline{Q}_L^5.\Sigma)(\Sigma^T.T_R^5) + \text{h.c.} \quad \Rightarrow \quad \mathcal{L}_{\rm Yuk} = \Pi_{LR}(q^2)s_h c_h \bar{t}_L t_R + \text{h.c.}, \tag{54.7}$$

where we assume, for simplicity, the momentum dependence of the form factor $\Pi_{LR}(q^2)$ can be approximated with a constant value $\Pi_{LR}(q^2=0)$. Clearly, $\Pi_{LR}(q^2=0)$ can be absorbed in the definition of the top quark mass, while the modification of the Yukawa coupling is given as [8]

$$k_t = \frac{g_{ht\bar{t}}}{g_{ht\bar{t}}^{\rm SM}} = \frac{1-2\xi}{\sqrt{1-\xi}} \simeq 1 - \frac{3}{2}\xi\,. \tag{54.8}$$

In the last equality, we make an expansion around small ξ. In the case of $\mathrm{MCHM}_{14_L-14_R}$ model (both left- and right-handed top quarks in **14** of SO(5)), however, more than one Yukawa invariants can be constructed. As a result of that, the form factors cannot be completely absorbed in the definition of top mass. The low energy Lagrangian in $\text{MCHM}_{14_L-14_R}$ with two invariants is given by

$$\begin{aligned}\mathcal{L}_{\text{Yuk}} &= \Pi^{(1)}_{LR}(\Sigma^T.\overline{Q}^{14}_L.T^{14}_R.\Sigma) + \Pi^{(2)}_{LR}(\Sigma^T.\overline{Q}^{14}_L.\Sigma)(\Sigma^T.T^{14}_R.\Sigma) + \text{h.c.}, \\ &= \left(\Pi^{(1)}_{LR} + \Pi^{(2)}_{LR}s_h^2\right) s_h c_h \bar{t}_L t_R + \text{h.c.} \end{aligned} \tag{54.9}$$

Modification of Yukawa coupling in this case is [9]

$$k_t = \frac{g_{ht\bar{t}}}{g^{\text{SM}}_{ht\bar{t}}} \simeq 1 - \left(2\frac{\Pi^{(2)}_{LR}}{\Pi^{(1)}_{LR}} - \frac{3}{2}\right)\xi\,. \tag{54.10}$$

Evidently, in this case, the coupling modification depends on the dynamics of the strong sector resonance states through the form factors. We comment in passing that, if either of t_L or t_R is embedded in the **14**, two Yukawa invariants can be constructed. The limit on f in $\text{MCHM}_{5_L-5_R}$ model at 95% CL, as obtained using the LHC data on the Higgs coupling measurements [10], is rather strong ($f \geq 1$ TeV), because k_V and k_t depends solely on a single parameter ξ. However, a relaxation on the limit on f is observed in models where more than one Yukawa invariants are present ($f \geq 640$ GeV) [9].

The modification of the Higgs couplings can also be captured using an effective field theory approach. In the strongly interacting light Higgs framework [6], the SM Lagrangian is extended with a set of gauge invariant dimension-six operators. For the illustrative purpose, we present a few of such operators which directly contributes to modify the tree level Higgs couplings. The kinetic term of the Higgs boson in this scenario containing dimension-4 and dimension-6 terms is given by

$$\mathcal{L}_{\text{kin}} = \left(D_\mu H\right)^\dagger (D^\mu H) + \frac{c_H}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H), \tag{54.11}$$

while the gauge and the Yukawa couplings of the Higgs boson is

$$\mathcal{L}_{\text{gauge}} = \frac{g^2}{2}(H^\dagger H)\left(W^+_\mu W^{-\mu} + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu\right), \tag{54.12}$$

$$\mathcal{L}_{\text{Yuk}} = -y_f \bar{Q}_L H t_R - \Delta\left(\frac{H^\dagger H}{f^2}\right) y_f \bar{Q}_L H t_R. \tag{54.13}$$

The modifications of the Higgs couplings upon electroweak symmetry breaking is then given by

$$k_V = \sqrt{1 - c_H\xi}, \quad k_t \simeq 1 + \left(\Delta - \frac{c_H}{2}\right)\xi. \tag{54.14}$$

Clearly, in $\text{MCHM}_{5_L-5_R}$ model $c_H = 1$ and $\Delta = -1$, while in $\text{MCHM}_{14_L-14_R}$ model Δ depends on the strong sector dynamics via the form factors.

54.3 Models with Extended Scalar Sector

In this section, we discuss the models where the SM particle content is extended with additional scalar fields. In general, singlet, doublet or triplet scalars can be accommodated with the existing Higgs doublet, with completely different phenomenological implications. In the context of composite Higgs scenario, non-minimal coset structures can lead to the presence of these additional scalars. For example, in next-to-minimal composite Higgs model (SO(6)/SO(5) coset) a singlet CP-odd particle is present [11]. Needless to mention that neutral component of the standard Higgs can mix with this additional singlet, and therefore, modifies the couplings of the 125 GeV Higgs boson. For example, the deviation of the Higgs couplings with the weak gauge bosons are suppressed by an additional factor of mixing angle θ_{mix} as given by [12]

$$k_V = \cos\theta_{\text{mix}}\sqrt{1-\xi}. \tag{54.15}$$

For the Yukawa part we write an effective operator as

$$\Delta\mathcal{L}_\eta \sim -y_t(\Delta_t^\eta)'\frac{\eta^2}{f^2}\overline{q}_L H^c t_R\,, \tag{54.16}$$

which leads to the coupling modification

$$k_t = \cos\theta_{\text{mix}}\left[1+\left(\Delta-\frac{c_H}{2}\right)\xi\right]+\sin\theta_{\text{mix}}\Delta_t^\eta\sqrt{\xi}. \tag{54.17}$$

This implies that LHC data can provide constraints in the plane of $\theta_{\text{mix}}-\xi$ plane, as shown in [9]. For details of effective field theory analysis in the singlet extended models and two Higgs doublet models see [13, 14]. On the contrary, adding a single triplet scalar with either hypercharge $Y=0$ or $Y=1$ leads to a severely constrained scenario from the electroweak precision data. However, in a Georgi-Machacek like model [15], where the $Y=0$ and $Y=2$ triplets are embedded in a (3, 3) under the $\mathrm{SU}(2)_L\times\mathrm{SU}(2)_R$, this constraint can be somewhat relaxed. We use such a setup and include dimension-5 operators in the Yukawa sector as [16]

$$\begin{aligned}-\mathcal{L}_{\text{Yuk}} = {} & \frac{c_5^t}{\Lambda}y_t\bar{Q}_L\chi^\dagger\phi t_R+\frac{c_5^b}{\Lambda}y_b\bar{Q}_L\chi\phi^c b_R+\frac{d_5^t}{\Lambda}y_t\bar{Q}_L\xi\phi^c t_R \\ & +\frac{d_5^b}{\Lambda}y_b\bar{Q}_L\xi\phi b_R+\text{h.c.}\end{aligned} \tag{54.18}$$

Note that, the inclusion of these additional terms modifies the 125 GeV Higgs couplings, as well as the couplings of the charged Higgs boson with the third generation quarks. This implies that the limits on the charged Higgs masses can be changed if we admit the existence of higher dimensional operators in the Gerogi-Machacek model, as shown in [16].

54.4 Conclusions

Composite Higgs is an interesting non-supersymmetric alternative to address the hierarchy problem of SM. One of the main features of these models is modifications in Higgs couplings which can be tested at LHC and proposed future colliders. Higher dimensional operators can capture the nonlinearity of pNGBs (e.g. strongly interacting light Higgs framework), which in turn, is responsible for the coupling modifications. The hVV modifications are generically universal, while the Yukawa coupling modifiers depend on the representation in which the fermions are embedded. Going beyond the minimal scenario one finds more pNGB scalars, for example, in the next-to-minimal model extra singlet scalar gives additional modifications due to neutral scalar mixing. Finally, dimension-five operators can have a significant impact on the constraints from flavour physics observables on the charged Higgs sector in triplet extended models (e.g. Georgi-Machacek model).

Acknowledgements This talk is based on the works done with Gautam Bhattacharyya, Nilanjana Kumar and Tirtha Sankar Ray, and I thank them for their valuable comments and discussions. I acknowledge the support provided by the Department of Atomic Energy, Government of India. Finally, I thank the organizers of XXIII DAE-BRNS High Energy Physics Symposium 2018, for the invitation.

References

1. D.B. Kaplan, H. Georgi, SU(2) x U(1) breaking by vacuum misalignment. Phys. Lett. B **136**, 183–186 (1984)
2. M.J. Dugan, H. Georgi, D.B. Kaplan, Anatomy of a composite Higgs model. Nucl. Phys. B **254**, 299–326 (1985)
3. R. Contino, The Higgs as a composite Nambu-Goldstone Boson, in *Physics of the large and the small, TASI 09, proceedings of the Theoretical Advanced Study Institute in Elementary Particle Physics*, Boulder, Colorado, USA, 1–26 June 2009 (2011), pp. 235–306
4. G. Panico, A. Wulzer, The composite Nambu-Goldstone Higgs. Lect. Notes Phys. **913**, 1–316 (2016) [1506.01961]
5. C. Csaki, P. Tanedo, Beyond the standard model, in *Proceedings, 2013 European School of High-Energy Physics (ESHEP 2013)*, Paradfurdo, Hungary, 5–18 June 2013
6. G.F. Giudice, C. Grojean, A. Pomarol, R. Rattazzi, The strongly-interacting light Higgs. JHEP **6**, 45 (2007) [hep-ph/0703164]
7. K. Agashe, R. Contino, A. Pomarol, The minimal composite Higgs model. Nucl. Phys. B **719**, 165–187 (2005) [hep-ph/0412089]
8. M. Montull, F. Riva, E. Salvioni, R. Torre, Higgs couplings in composite models. Phys. Rev. D **88**, 095006 (2013) [1308.0559]
9. A. Banerjee, G. Bhattacharyya, N. Kumar, T.S. Ray, *Constraining composite Higgs models using LHC data*. JHEP **1803**, 62 (2018) [1712.07494]
10. ATLAS, CMS collaboration, G. Aad et al., Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV. JHEP **8** 45 (2016) [1606.02266]
11. B. Gripaios, A. Pomarol, F. Riva, J. Serra, Beyond the minimal composite Higgs model. JHEP **04**, 070 (2009) [0902.1483]

12. A. Banerjee, G. Bhattacharyya, T.S. Ray, Improving fine-tuning in composite Higgs models. Phys. Rev. **D96**, 035040 (2017) [1703.08011]
13. M. Chala, G. Durieux, C. Grojean, L. de Lima, O. Matsedonskyi, Minimally extended SILH. JHEP **6**, 88 (2017) [1703.10624]
14. S. Karmakar, S. Rakshit, Higher dimensional operators in 2HDM. JHEP **10**, 48 (2017) [1707.00716]
15. H. Georgi, M. Machacek, Doubly charged Higgs Bosons. Nucl. Phys. B **262**, 463–477 (1985)
16. A. Banerjee, G. Bhattacharyya, N. Kumar, Impact of Yukawa-like dimension-five operators on the Georgi-Machacek model. Phys. Rev. **D99** 035028 (2019) [1901.01725]